LANSCE DIVISION TECHNOLOGY REVIEW

Residual Strains In a Pigma-Welded Beryllium Ring

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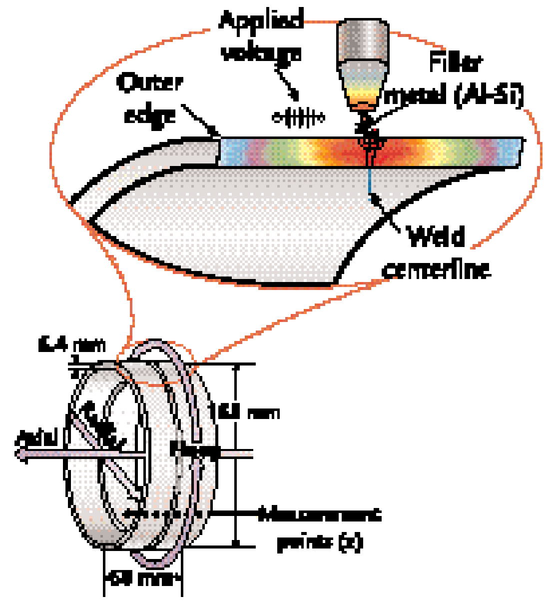
Introduction

The thermal, mechanical, and neutronic properties of beryllium make it highly attractive for applications in defense, space, and nuclear energy. Used in metallurgy as a hardening agent, this alkaline-earth metal has a relatively high melting point, conducts electricity, exhibits moderate mechanical properties at elevated temperatures, is noncombustible, and has a high modulus of elasticity (a measure of the ability of a material to withstand changes in dimensions when under tension or compression). However, joining beryllium to itself or to other materials is a challenge because of the metal's propensity to crack as a result of fabrication processes like welding or brazing. Filler metals such as silver or aluminum have been successfully used to bond beryllium parts, but the process involved, known as Pressurized Inert Gas Metal Arc (PIGMA) welding, introduces residual stresses that become locked into the post-welded base metal. Residual stresses play a major role in the thermal or mechanical failure of a fabricated part (i.e., the fatigue lifetime of the part). LANSCE Division supported researchers from the Materials Science and Technology Division, Oak Ridge National Laboratory, and ISIS (the Rutherford-Appleton Laboratory Neutron Facility) in experiments aimed at measuring residual stresses in welded cylindrical beryllium rings (Fig. 1). The ultimate goal of the investigation was to validate and improve on currently used finite element models (FEMs)—discrete mathematical models used to predict stress and strain in a part and ultimately estimate at what point the part will fail.



▲ ***Fig. 1.*** *Schematic of PIGMA-welded beryllium rings, showing the hoop, radial, and axial directions and measurement positions (z). The cutaway shows a portion of the welded beryllium rings. In metal-arc welding, a current between the filler metal (anode) and the base metal (cathode) melts the filler metal, which then settles in the trough and space between the beryllium rings and welds the two separate parts together. The base metal near the weld centerline heats up and expands (red), but the outer edges of the metal remain cool (blue).*

Effects of PIGMA Welding on Beryllium Rings

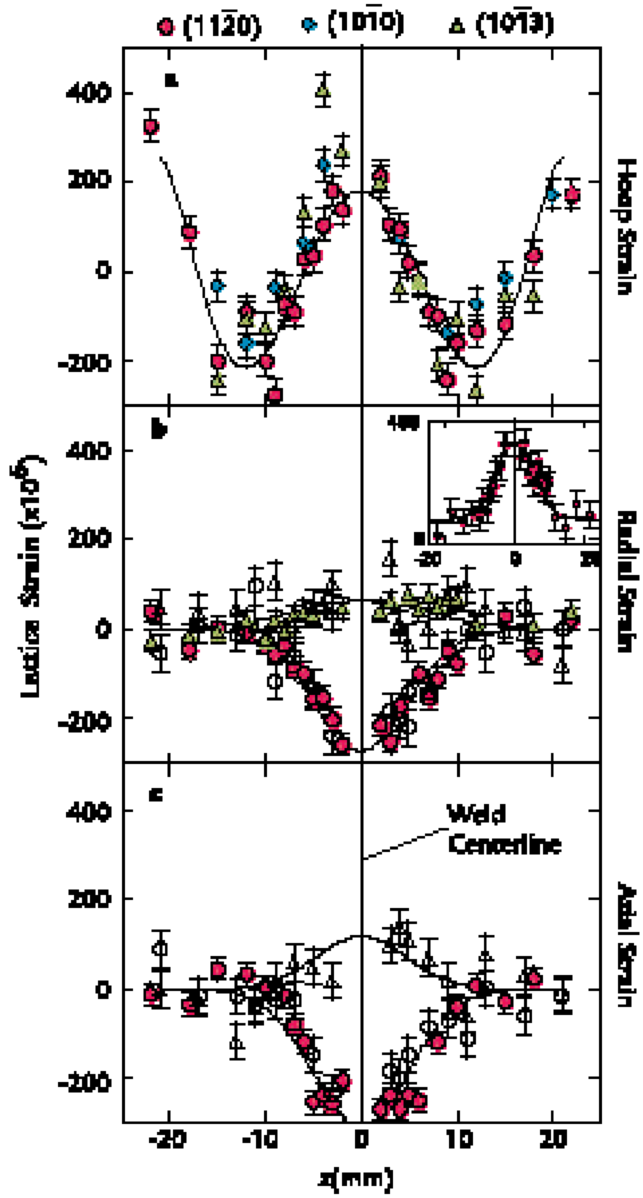
In metal-arc welding, a current between the filler metal (anode) and the base metal (cathode) melts the filler metal, which then settles in the trough and space between the beryllium rings (see Fig. 1) and joins the two separate parts. The base metal near the weld centerline heats up and expands (red), but the outer edges of the metal remains cool (blue). Residual stresses develop because of the difference in the thermal expansion of the filler material and base metal and because of the spatially localized differential heating of the base metal. The base metal near the weld centerline expands, develops stress, yields (relaxes the stress), shrinks as it cools, and becomes rigid. During this process, however, the outer edges of the base metal remain cool, which constrains the hot metal as it expands, cools, and becomes rigid. The outer edges are thus placed in a state of compression while at the same time the region near the weld is placed in a state of tension.

Optimizing the fabrication procedure by welding a large suite of parts is prohibitively expensive. Oftentimes FEMs can be used instead in less time and at much lower costs to predict the thermal or mechanical lifetime of a part. FEMs developed by the Accelerated Strategic Computing Initiative and by the Engineering Sciences and Applications Division predict residual stress-strain fields, but inevitably these models need experimental validation.

Neutron Diffraction Techniques Offer Insight into Large-Scale Plasticity in Post-Welded Beryllium Rings

Using spatially resolved neutron diffraction techniques at LANSCE, we determined residual strains as a function of axial distance from the weld centerline (see Fig. 1) by measuring both the interplanar spacings of the (10$\bar{1}$0), (11$\bar{2}$0), and (10$\bar{1}$3) crystallographic planes in the beryllium base metal and the distinct lattice vectors **a** (the distance between the nearest-neighbor atom in the basal plane) and c (the distance between two basal planes). The mechanical properties of the base metal are different (anisotropic) in the a direction and in the **c** direction. Figs. 2a, b, and c show the observed residual strains in the hoop, radial, and axial directions (see Fig. 1), respectively. The base metal exhibited significant tensile residual strain in the hoop direction near the weld centerline—a result consistent with localized differential heating of the beryllium base metal. Maximum tensile strain near the weld centerline was caused by residual stress of roughly 60 MPa, or about 20% of the ultimate tensile strength of beryllium. Also, significant plasticity-induced anisotropy (i.e., direction-dependent behavior produced by plastic deformation whereby changes in the microstructure of the base metal are irreversible) was observed within ±10 mm of the weld centerline in both the axial and radial directions. This anisotropic behavior was indicated by the separation of the residual strains determined in the (11$\bar{2}$0) and (10$\bar{1}$3) crystallographic planes. Both of these results indicate that the base metal experienced plastic deformation during the weld procedure. This point is particularly significant because the FEM results failed to predict large-scale plasticity in the base metal during the weld procedure. This failure is likely due to a lack of understanding of the heat-flow process that occurs during the deposition of the filler metal in the PIGMA weld process.

We believe that the source of the observed residual strains and plastic deformation is the thermal gradient, which is induced between the weld and the edges of the rings during the PIGMA weld process. As mentioned earlier, when the metal near the weld is hot, it becomes relatively soft and ductile. However, the cooler metal near the edge remains rigid. The hot metal expands, but it is constrained by the cooler metal at the edge and thus deforms plastically, resulting in the observed anisotropy strain near the weld. On cooling, at some point the metal near the weld regains its rigidity, but it continues to shrink as it cools, while the metal near the edge once again acts as a constraint. This process places the metal near the weld in residual tension and cooler outer edges in a state of residual compression.



▲ ***Fig. 2.*** *(a) Hoop, (b) radial, and (c) axial directions of the lattice-specific strain are plotted as a function of distance from the weld centerline. Closed and open symbols represent data taken on the reactor and spallation sources, respectively. The solid lines are guides for the eye.*

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